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# Recent trends in PEM fuel cell-powered hybrid systems: Investigation of application areas, design architectures and energy management approaches

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ABSTRACT

Recently, the renewable energy issue is becoming significant due to increasing power demand, instability of the rising oil prices and environmental problems. Among the various renewable energy sources, fuel cell (FC) technology has received considerable attention as an alternative to the conventional power units due to its higher efficiency, clean operation and cost-effective supply of power demanded by the consumers. Particularly, proton exchange membrane (PEM) FC technology plays a leading role for many applications when comparing with other competitive types of FCs. PEMFCs have recently passed the test or demonstration phase and have partially reached the commercialization stage due to the impressive worldwide research effort. Besides, providing a hybrid system by integration of PEMFC with an auxiliary power source may provide better results considering the issues of performance and component durability. This paper presents a comprehensive review of the recent trends in PEMFC powered hybrid systems including a detailed explanation of application areas and design architectures with different power electronics interfaces as well as the energy management methods utilized in the daily life and taking part in the literature.



**Contents**



## 1. Introduction

Ever increasing energy consumption causing the depletion of fossil fuels and rising public awareness for environmental protection result much of the research work to focus on alternative/renewable energy sources recently. As a consequence, novel renewable and clean energy power sources must be considered. One of the prevalent alternative sources of electric power is the fuel cell (FC) technology in the context of decreasing oil resources and hazardous $CO_2$ emissions [1]. An FC is an energy conversion device that converts the chemical energy of a reaction

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directly into electricity with by product of water and heat. There are several types of commercially available FCs, such as proton exchange membrane (PEM) FCs, solid oxide FCs, alkaline FCs, direct methanol FCs, etc. Among the various types of FCs, the PEMFC technology has found widespread use of area especially in vehicular applications, distributed generation (DG) units and portable electronic equipments [2]. Some of the key advantages and some disadvantages of PEMFC systems over the other competitive types of FCs can be specified as follows [1]:

Advantages:

- They can operate at relatively low temperatures.
- They are tolerant of $CO_2$; so they can use the atmospheric air.
- They have high voltage, current and power density.
- They can work at low pressure (1 or 2 bars), which adds security.
- They have a good tolerance to the difference of pressure of the reactants.
- They are compact and robust.
- They have a simple mechanical design.
- They use stable building materials.

Disadvantages:

- They are very sensitive to impurities of hydrogen.
- They need humidification units of reactive gases.
- They use very expensive catalyst (platinum) and membrane (solid polymer).

The PEMFC technology is still under investigation of many researchers for powering systems in many applications. However, the daily operation of systems like vehicular loads and residential units with transient load changes may not be suitable for using a sole PEMFC system. This phenomenon is mainly caused by the reason of the limitation of FCs to track fast load variations due to their slow dynamics. These fast energy demand periods frequently occurring in the operation of daily utilized systems will cause a high voltage drop in a short time, which is defined as starvation phenomenon [1]. In the case of the fuel or oxygen starvation, the FC performance degrades, and the cell voltage drops. This issue may cause a significantly insecure operation for the FC stack. Fuel starvation can result in production of hydrogen in the cathode as well as oxygen in the anode. For instance, in the case of hydrogen starvation, the cell current cannot be maintained, causing a high anode potential. Therefore, the water, which is present at the anode, may split into hydrogen and oxygen, producing oxygen in the anode. Similarly during oxygen starvation, the reaction at the cathode will produce hydrogen. The presence of oxygen at the anode and hydrogen at the cathode will lead to the reversal of the cell potential, which is a negative potential difference between the anode and the cathode. Cell reversal accelerates the corrosion of carbon components in the cell and eventually leads to a damaged structure. [3]. Thus, to utilize an FC in dynamic applications, its current or power slope must be limited to prevent the fuel-starvation problem. It is therefore recommended, when utilizing a PEMFC, to associate it with, at least, an auxiliary power source to improve the dynamic performances of the whole system. There are many types of auxiliary units for compensating the slow response characteristics of the PEMFC unit and increasing the efficiency of the overall system. Energy storage units such as batteries, ultracapacitors (UCs), flywheels, etc. and secondary power units like micro-turbines, diesel generators, etc. can be classified in the auxiliary power units group for use in hybrid systems including PEMFC. Specifically, energy storage units not only compensate the slow response phenomenon of PEMFC system, also provides the advantage of recovering the re-usable kinetic energy occurring in vehicular applications while braking periods. Thus, the consumption of hydrogen for FC units can significantly be decreased.

Because of different characteristics of multiple power sources in a PEMFC powered hybrid system, the efficiency and the fuel economy of these hybrid units mainly depend on a proper energy management strategy and well-designed power electronics architecture. There are many contributions of the researchers to the literature considering the mentioned energy management and design architecture issues. Thus, it is aimed that this paper may be useful for researchers to understand the recent trends about managing the energy flow and designing the power electronics based topology for PEMFC powered hybrid systems.

The organization of this paper is as follows. Section 2 describes the most common application areas of PEMFC powered hybrid systems. Section 3 presents different types of hybrid system design architectures with necessary literature examples. Section 4 similarly clarifies the lately utilized energy management approaches in the literature. Finally, conclusions are given in Section 5.

## 2. The most common applications of PEMFCs

Due to the fact that PEMFCs can generate power from a few Watts to hundred kilo-Watts with providing environmental-friendly operation, they can be used in almost every application where local electricity generation is needed. This subsection clarifies the most common applied areas of PEMFCs in recent times as follows:

### *2.1. Transportation area*

The most common alternative drivetrain, which is not based on the internal combustion engine (ICE), is that of a battery electric vehicle. Electric vehicles are widely used where the noise or pollution of internal combustion engines prohibits their application, e.g. in the case of indoor or mining vehicles, but also in the absence of air, e.g. in the case of underwater or lunar vehicles. Major shortcomings of this alternative are attributed to the electric energy storage; namely the too low capacity, high cost, long charging time, small operating temperature range and low cycling stability. These insufficient properties have prevented their wider use for propulsion of passenger vehicles [4].

FCs offer many advantages over the internal combustion engines (ICE) for vehicular applications because they are energy efficient, clean, and fuel flexible. Hydrogen FC systems have the potential to reach 60% peak efficiency on lower heating value (LHV) basis. On-board the vehicle, conversion of hydrogen to traction power produces water only. Hydrogen can be produced from a variety of sources including fossil fuels such as natural gas, renewables such as solar and wind power, biomass, and nuclear energy [5].

Automobiles, buses, scooters, golf cars, utility vehicles (such as forklifts and airport vehicles), locomotives, tramways, boats, airplanes, underwater vehicles can be clarified as some of the applications of PEMFC systems in transportation area. Especially in automobile systems, almost all major car manufacturers have demonstrated prototypes of FC vehicles and announced future plans for production and commercialization in the near future [6]. On the other hand, buses seem to be the most likely type of road vehicles for an early market introduction of the FC technology. Also, scooters may be a significant market for FC technologies, especially in developing countries. To conclude, the transportation area seems to be the most promising sector of PEMFC technology.

### *2.2. Distributed generation*

The small-scale generation systems such as wind turbine, photovoltaic, micro-turbines, and FCs play an important role to

meet the consumers demand using the concepts of DG. The term DG means any small-scale generation unit located near to the customers rather than central or remote locations. The major benefits of DG systems are saving in losses over the long transmission and distribution lines, installation cost, local voltage regulation, and ability to add a small unit instead of a larger one during peak load conditions [7].

PEMFC systems have been installed worldwide in many types of distributed centres such as hospitals, shelters, centers for elderly care, hotels, offices and schools [1]. Moreover, PEMFC technology has found application area in the field of telecommunications, where there is a need for a fully reliable electricity supply [8]. In these cases, the PEMFC system is connected to the grid to provide additional electrical power to the plant, or as an independent system of the grid to generate electricity in remote or isolated areas. The use of PEMFC in such systems may either be as a main power source or as a ''back-up'' unit. The following subsections clarify the mentioned usage modes of PEMFC system in DG applications:

#### 2.2.1. Use of PEMFCs as main power source

The use of PEMFC as main power source in DG systems is an attractive solution as considered by many researchers providing contributions to the literature on this issue [8–11]. There are two types of approaches for this type of application of PEMFCs: the PEMFC system can either be combined with an energy storage unit such as battery, UC, etc. [9–11] or a secondary main power unit such as micro-turbine, diesel generator, etc. [8,12] as auxiliary power source. The needed hydrogen for PEMFC unit in such systems is generally supplied by a reformer unit with the supplement of inlet fuel such as natural gas. A general scheme for such systems can be seen in Fig. 1.

#### 2.2.2. Use of PEMFCs as back-up unit

''Back-up power'' term is defined as any device that provides instantaneous, uninterruptible power when the main power sources are not available or unable to meet the power demand. The usage of PEMFC technology in DG systems as back-up unit generally depends on a topology where the renewable power sources such as wind turbine for wind energy, photovoltaic (PV) panels for solar energy are main power sources and the FC unit is utilized via an electrolyzer system. A diagram of such a hybrid topology is shown in Fig. 2. The main power sources in such systems generate output power due to meteorological conditions. If there is an excess power, this power is utilized for generating hydrogen via an electrolyzer and stored in hydrogen tanks for future use in FC system. Besides, FC system generates output power in the periods where output power values of main power sources are not sufficient for supplying load demand. Thus, the conventional use of huge battery units as main back-up in such systems can be replaced with a more environmental-friendly, economic and reliable technology [7]. There may also be an additional small-sized storage unit, grid connection, etc. if required or desired. It is to be noted that if no grid connection is provided, this kind of system is called a ''stand-alone'' system. The use of PEMFC system as ''back-up'' in DG applications has also found a great area in the literature [7,13–28].

### 2.3. Portable applications

FCs can provide electrical power in places where the grid connection is not available and can be used as portable power units. For example, in a vacation place outdoors (camping area), the use of an FC for electrical power instead of a diesel generator avoids harmful emissions and causes no problems of noise in the environment. Also, FCs are being used as supporting units when power shutdowns occur and in military applications. FCs are much lighter and more durable than batteries, which are particularly important for the soldiers during periods of military maneuvers, and even more in case of war. Some applied areas of FCs in portable military applications include battery chargers, navigation systems, sensors, etc. [5]. Moreover, the use of PEMFCs for portable computers (laptops) and mobile phones is recommended lately and this idea has found a widespread attention from manufacturers. The researches of reputed companies such as Motorola, Toshiba, Samsung, Panasonic, Sanyo, and Sony have shown that mobile phones can be run for twice as long as compared to the one that uses a lithium battery with an equivalent size and it needs only 10 min to recharge. As far as laptops are concerned, it has been shown that laptops with FCs may be working up to 5 h without refuelling [29]. These types of FCs used in laptops or mobile phones are called ''microFCs''. Other applications for microFCs include pagers, hearing aids, smoke detectors, security alarms, etc. This area of usage for PEMFCs is still under investigation and is a serious candidate for future wide use of PEMFC technology.

### 2.4. Main challenges to more use of PEMFCs in daily life

Many factors have limited the marketable development of FCs, including manufacturing cost, fuel generation and distribution, and system complexity and durability. The high manufacturing

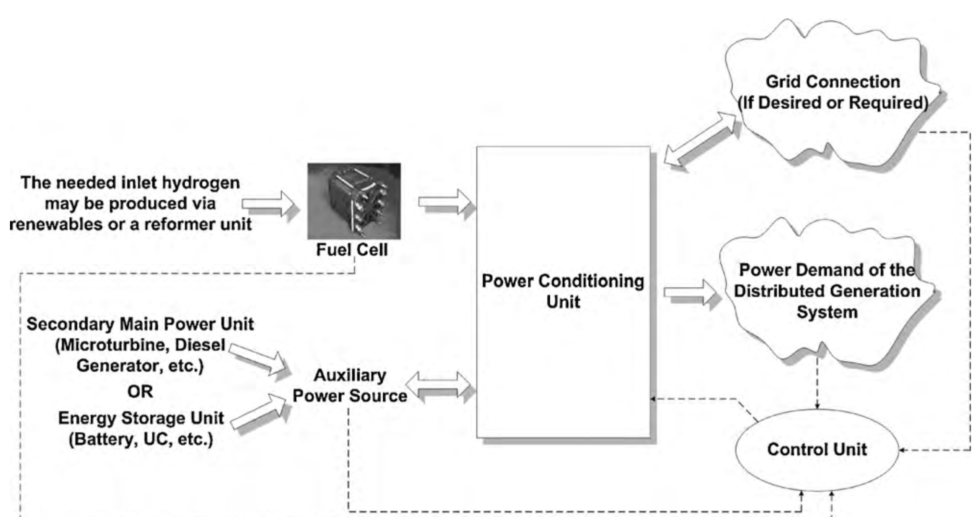


**Fig. 1.** A general scheme of a hybrid DG system with the use of PEMFC as main power source.

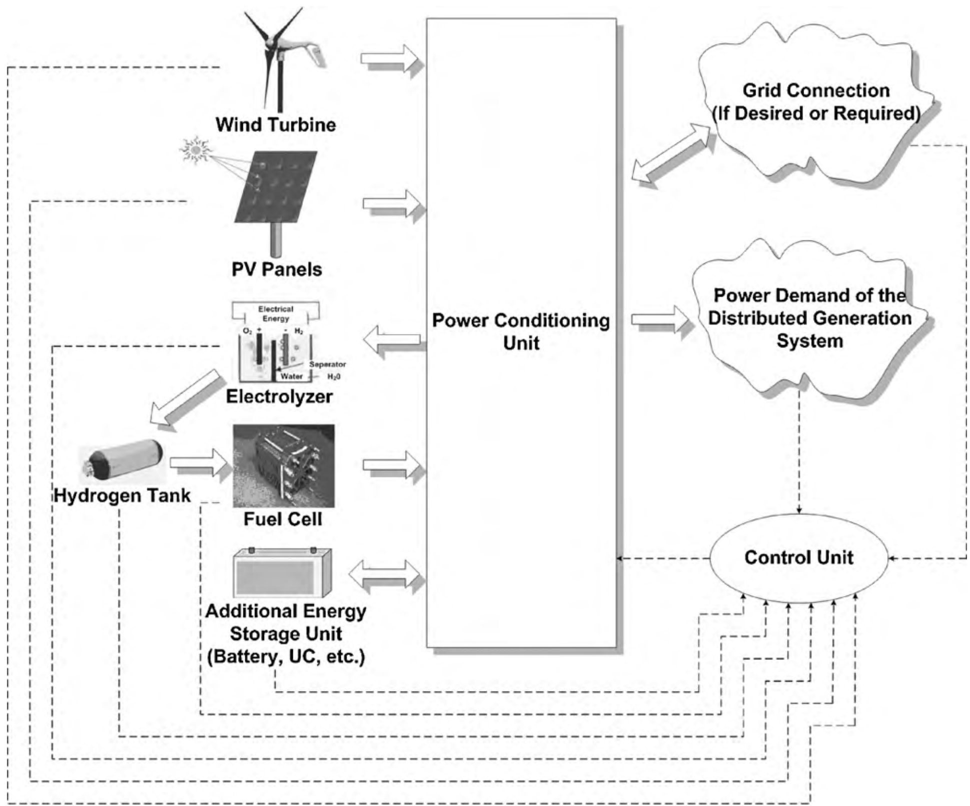


**Fig. 2.** A general scheme of a hybrid DG system with the use of PEMFC as back-up unit.

cost is caused by a number of factors: expensive raw materials used as catalysts, expensive membrane materials, and expensive fabrication processes for collector plates. In addition to manufacturing cost, fuel generation and distribution have also prevented widespread commercialization. Most FCs consume pure hydrogen or hydrogen-rich gas as the primary fuel. So far, experimental results and real-world applications of PEMFCs revealed that they perform best on pure hydrogen as anode input gas. However, for many applications, particularly mobile, due to the lack of availability of refuelling infrastructure and impractical storage techniques, pure hydrogen is not yet a viable option [30]. Thus, production, distribution and storage of hydrogen may be a challenging issue especially when considering the high costs of necessary equipments for the abovementioned activities [6]. In short, wider use of PEMFCs can only be expected when a number of important and rather complex problems are solved which can be summarized as follows [5]:

- Longer lifetime for power plants and better stability of the catalysts and membranes.
- Lower cost of production for the PEMFC systems, which can be realized by the development of catalysts without platinum with the use of alternative structures such as carbon nanotubes and cheaper membranes.
- The development of new plants for hydrogen production admitting a wider selection of primary fuels.
- Providing more numbers of refuelling stations especially for vehicular applications.

## 3. Design architectures for PEMFC powered hybridizations

Interfacing the load unit requirements with the different operation modes of on-board generation and storage units call for suitable power electronic converter configuration and control. The selection of power-conditioning unit for hybrid systems including PEMFC is based on some significant factors like lower cost, higher efficiency, electrical isolation, ripple free and reliable operation.

Considering the above-mentioned factors as well as the load requirements due to the use of area, various topologies may be used for the operation of PEMFC hybrid systems. One of the most simple structures for the parallel operation of PEMFC hybrid systems includes the direct integration of PEMFC system with the auxiliary power unit as shown in Fig. 3. During low power demand, the FC system generates up to its load limit, and the excess energy between the load demand and the FC output power is used to charge the auxiliary unit. In this period, the S1 switch is closed and S2 switch is open. Besides during high power demand periods, both the FC system and the auxiliary units supply the load demand. During this period, S1 switch is kept open and S2 switch is closed. The direct integration topology is attractive, because it does not require a high power DC/DC converter, thus the complexity, cost, weight, and volume of the system are significantly reduced. This topology is proposed by Honda [31] for a combined PEMFC/UC powered vehicular system. Uzunoglu and Alam [10,32] utilized this topology for a stand-alone system, while Yalcinoz and Alam [2] applied the same topology for portable applications. Besides, the same topology is also utilized by Onar et al. [13] as a part of his study for the combination of FC and UC in a Wind Turbine/PEMFC/UC hybrid system for stand-alone applications.

Different designs of a topology with only one DC/DC converter unit are shown in Figs. 4 and 5. The topology in Fig. 4 regulates the output power of the FC system while the rest of the energy between the load demand and the FC output power is naturally supplied by the auxiliary unit. Besides, the topology in Fig. 5 is based on the regulation of the auxiliary system output power or the regulation of the DC bus voltage. There are many studies in the literature using these two topologies. Topology in Fig. 4 is utilized

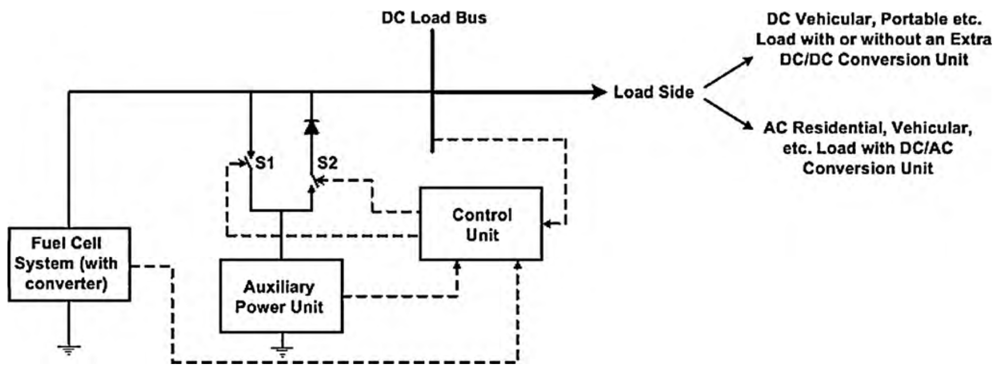


**Fig. 3.** Direct integration topology.

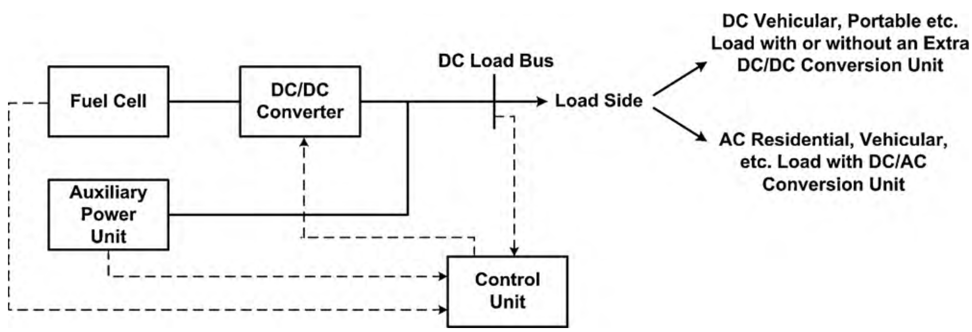


**Fig. 4.** Single converter based topology (Type-1).

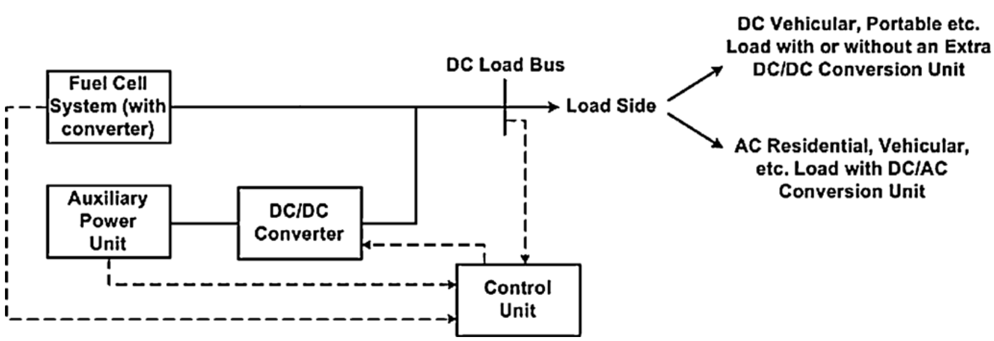


**Fig. 5.** Single converter based topology (Type-2).

by Jiang et al. [33] for PEMFC/Battery hybridization, by Xu et al. [34] for PEMFC/Battery powered city bus, by Fontela et al. [35] for an airport vehicle powered by PEMFC, by Sripakagorn and Limwuthigraijirat [36] for a PEMFC/UC hybrid scooter, etc. Moreover, the second topology in Fig. 5 is applied by Payman et al. [37] for PEMFC/UC hybridization while the same hybridization structure is also employed by Chen et al. [38].

The most common topology in the literature for hybrid systems is composed of multiple DC/DC converters as seen in Fig. 6. In this kind of topology, the DC/DC converter of one of the available power sources is employed for the DC bus voltage regulation which is called "voltage-oriented-control", and the rest of the converters are controlled for power tracking by "power-oriented-control" methodology. Thus, the proposed power-conditioning unit pro-

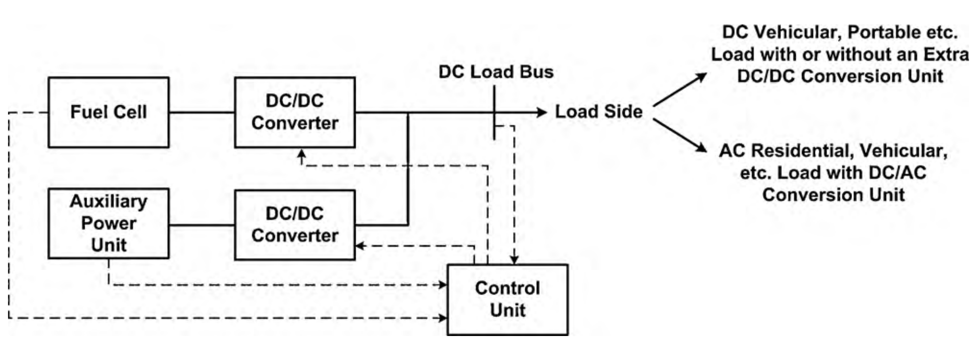


**Fig. 6.** Multiple converter based topology.

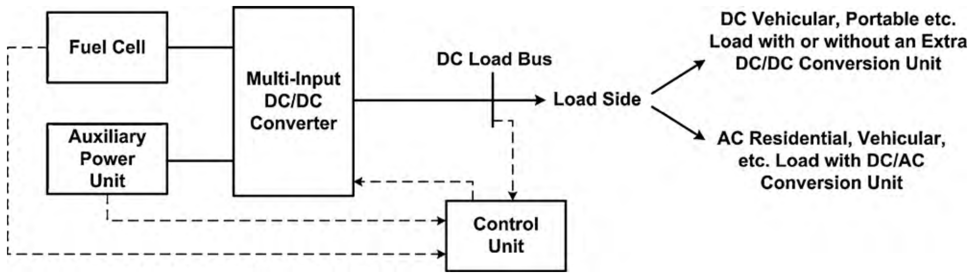


**Fig. 7.** Multi-input converter based topology.

vides the capability of delivering the desired power value from the hybrid power sources while keeping the bus voltage in a desired level. This topology has been applied in different areas. The studies of Zhang et al. [39], Erdinc et al. [40,41], Thounthong et al. [30,42] and Feroldi et al. [43] are some of examples for the usage of multiple converter topology for transportation area. Besides, the studies of Thounthong et al. [9,11] can be the examples from the DG systems area for this hybridization structure. Stewart et al. [44] also utilized this topology for a DG unit where the needed hydrogen for FC system is obtained using an electrolyzer and solar energy unit in series connection.

Combining the features of the multiple converter based topology, some researchers focused on utilizing a multiple-input single-output design architecture as seen from Fig. 7. This topology provides the advantage of reduction in number of elements (multiple inputs of power sources can be connected to a DC bus via only one output capacitor) used in power electronics interface design. The literature survey on multi-input converter topology usage results in some example studies using PEMFC unit. For example, Ferreira at al. [45], Perez et al. [46] and Napoli et al. [47] utilized the multi-input converter topology for an electrical vehicular system consisting of PEMFC, battery and UC. Besides, Onar et al. [8] applied a similar topology for a telecommunication system powered by PEMFC and micro-turbine.

The above-mentioned topologies are generally presented for the applications that the PEMFC system is utilized as main power source. However, a specific classification can be realized for DG systems that the renewable energy sources such as wind and solar are utilized as the main power source and the FC system is employed as back-up unit. The mentioned combination is generally realized with a multiple converter use as shown in Fig. 8. It is to be noted that each main power source (wind, solar, etc.) in the mentioned combination may also have an extra converter unit for maximum power tracking, etc. purposes. Many studies using this kind of design for DG system take place in the literature: the studies of Pedrazzi et al. [15], Lagorse et al. [17], Uzunoglu et al. [18] for a PV/FC hybrid system, Samaniego et al. [16], Khan and Iqbal [21] for Wind/FC hybridization and Onar et al. [19], Kaviani et al. [20], Wang and Nehrir [7] for a Wind/PV/FC hybrid structure may be presented as only a small part of examples from the literature.

The DC/DC converter systems utilized in the above-mentioned studies may have several architectures and power electronics area researchers still search for a better efficiency and reduction in number of elements in the converter design. The design of the above-mentioned single or multi-input converters can be realized as insulated or un-insulated, unidirectional or bidirectional according to the use of area. The basic un-insulated unidirectional and bidirectional DC/DC converter topologies are shown in Fig. 9. However, there are different advanced, more advantageous but complex topologies developed by power electronics researchers. Some of the different unidirectional and bidirectional (for use in auxiliary power units such as battery, UC) converter topologies in the literature and their detailed mathematical and electrical explanations can be found in the studies of Liu and Li [48], Thounthong et al. [49], Khan and Tolbert [50], Farzanehfard et al. [51] and Solero et al. [52].

## 4. Energy management approaches

Due to the different characteristics of multiple power sources, the efficiency and the fuel economy of hybrid systems mainly depend on a proper energy management strategy (EMS). It is widely accepted that frequent operation of transient regulation of the FC stack increases the mechanical stresses inside the FC, and consequently decreases the stack lifetime. On the other hand, in the operation of the FC system, continual regulation of state variables (such as reactant flow and stack temperature) directly leads to more stringent requirements for dynamic responses of actuators (valves, motors, etc.) and sensors (pressure, flow rates,

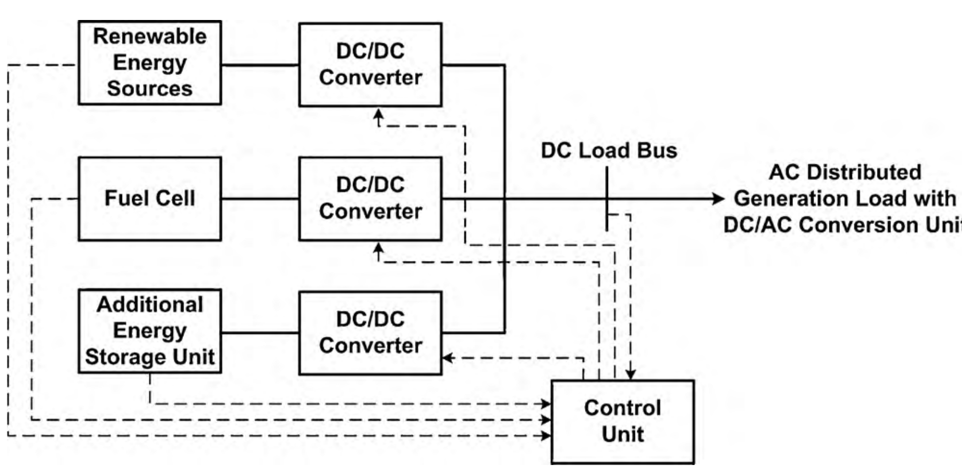


**Fig. 8.** Multiple converter based specific topology for DG systems.

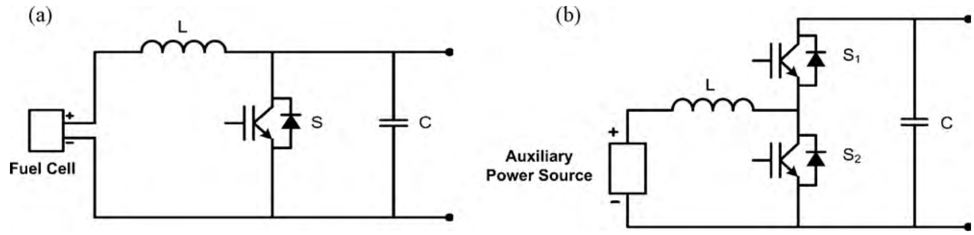


**Fig. 9.** Structures of the basic DC/DC converter topologies: (a) Boost converter topology and (b) bidirectional converter topology.

temperatures, humidity, etc.), and potentially increase the cost of the overall system. Therefore, it is necessary to keep the stack in a steady state and supply a stable power during the variable load operation. Thus, the energy management issue shows a significant importance in PEMFC powered hybrid systems. For better understanding of the energy management strategies of hybrid systems with multiple on-board power sources, numerous studies realized by various authors can be found in the literature. This section clarifies the lately applied energy management approaches for PEMFC powered hybrid systems.

### 4.1. Intelligent-based energy management strategies

Lately, there exist many studies using intelligent-based energy management strategies such as fuzzy logic, and neural networks for use in PEMFC powered systems. Among them, fuzzy logic controller (FLC) based methodology has a major position due to its independence of a full mathematical plant model and training procedure. FLC provides a remarkably simple way to draw definite conclusions from vague, ambiguous or imprecise information. Unlike classical logic which requires a deep understanding of a system, exact equations, and precise numeric values, fuzzy logic incorporates an alternative way of thinking, which allows modeling complex systems using a higher level of abstraction originating from our knowledge and experience. Nonlinearity and difficulties in proper identification of parameters of the plant mathematical models limit the use of model based conventional control approaches. Fuzzy logic provides a quite suitable structure compared to conventional control methods especially for the systems composed of nonlinear behaviors where an overall mathematical model is difficult to obtain. Moreover, there is no need for historical data, which is an important advantage over other types of "intelligent" controllers such as neural networks. Thus, FLC provides a pretty suitable structure especially for the systems composed of nonlinear behaviors.

In the literature, many researchers focused on fuzzy logic approach and applied to hybrid systems with PEMFC for different applications. Among them, Gao et al. [53] provided the power distribution in a "hydrogen" powered hybrid bus composed of PEMFC as the main power source and battery/UC combination as the auxiliary unit. The FLC applied in Ref. [53] utilized the SOC values of auxiliary units and the required power demand of the bus as inputs for determining the output power values of FC and UC systems. Erdinc et al. regulated the energy management in PEMFC/UC and PEMFC/Battery/UC powered hybrid vehicular systems using fuzzy logic in Refs. [40,41]. Both fuzzy structures of Erdinc et al. utilized the SOC values of battery and/or UC units and a transient-free form of the vehicular power demand (provided by a load sharing algorithm) based on standard drive cycles as inputs and gave the requested power value from PEMFC system as output. Li and Liu [54] proposed a FLC design for a PEMFC/Battery hybrid system with a similar structure to Erdinc et al. [41], however they optimized the parameters of their FLC for an optimal energy control. As a contribution to the mentioned studies of Erdinc et al. [40,41] and Li and Liu [54], Eren et al. [55] inserted the control of internal dynamics of PEMFC system in the fuzzy logic based energy management approach in order to better provide a safe and efficient operation for PEMFC. Eren et al. controlled both the power distribution in the hybrid structure and the oxygen excess ratio of PEMFC as the outputs of the FLC. Different from the above-given studies, Kisacikoglu et al. [56] directly controlled the duty cycles of the converters of PEMFC and UC as the outputs of the FLC in a PEMFC/UC hybrid vehicular system. In addition to the above-mentioned studies, there are also many researchers such as Li et al. [57], Jeong et al. [58], and Ferreira et al. [45], who investigated the feasibility of fuzzy logic approach for transportation based (vehicles, buses, etc.) applications of PEMFC powered hybrid systems. In a different application, Stewart et al. [44] applied the fuzzy logic approach to a "hydrogen house" application consisting of photovoltaic (PV) panels, PEMFC system and battery banks. FLC of Steward et al. [44] was mainly based on the control of power distribution between PEMFC, battery and the grid connection whenever it is necessary. Another DG application of PEMFC system where fuzzy logic is utilized is realized by Bilodeau and Agbossou [14] for a Wind Turbine/PV/PEMFC/Battery hybrid stand-alone system. All of these studies and many other studies not mentioned here contributed the application of fuzzy logic based energy management approaches for PEMFC powered systems from different points of view.

Another intelligent method used for the control of hybrid system is the neural network approach. Neural network models are computer programs that are designed to emulate human information processing capabilities such as knowledge processing, speech, prediction, classifications, and control. The ability of neural network systems to spontaneously learn from examples and to provide adequate and quick responses to new information which are not previously stored in memory has generated increasing acceptance for this technology in various engineering fields. As comparing neural network with one of the most popular intelligent-based technique, fuzzy logic, this quick response capability provides a significant advantage. Fuzzy logic approach does not need a training procedure, however the rule-based fuzzy structure makes it longer to response compared to neural network approach. Thus, neural network control may be a competitive approach with fuzzy logic in some points. Besides, the above-mentioned features would lead the neural networks to solve complex problem methods precisely and flexibly, and provide a suitable basis for the control of complex systems. Therefore, neural network has demonstrated remarkable success in control area.

Some studies, not much as fuzzy logic, utilizing the neural network approach for energy management can be found in the literature. Ates et al. [59] provided a neural network supervisory controller for vehicular systems as well as the study of Prokhorov [60]. Azmy and Erlich [61] managed the operation of a PEMFC system for residential applications using neural networks. A methodology using Quasi-Newton algorithms based neural networks was presented by Hatti and Tioursi [62].

To conclude this subsection, it can be summarized that the intelligent-based controllers are the most remarkable and the most

utilized energy management strategies in the literature for the applications of hybrid systems including PEMFC.

### 4.2. Optimization based strategies for energy management

In these types of energy management approaches, the optimal reference power signals for the on board power sources are calculated by minimization of a cost function. This mentioned cost function generally represents the fuel consumption or emissions especially for vehicular applications. If this optimization is performed over a fixed driving cycle, a global optimum solution can be found. Many approaches such as optimal control theory, linear programming, dynamic or stochastic programming, genetic algorithm, simulated annealing, linear and nonlinear model predictive, and game theory are utilized for solving the aforementioned global optimization problem. In fact, the global optimal solution is non-casual in that it finds the minimum fuel consumption using knowledge of future and past power demands. Obviously, this approach cannot be used directly for real-time energy management; however, it might be a basis of designing rules for online implementation or comparison for evaluating the quality of other control strategies. On the other hand, by definition of an instantaneous cost function, a real-time optimization-based control strategy can be found. Such a function has to depend only upon the system variables at the current time. The instantaneous cost function should include an equivalent fuel consumption to guarantee the self-sustainability of the electrical path. Of course, the solution of such a problem is not globally optimal, but it can be used for real-time implementation.

There is remarkable number of studies dealing with the energy management of an FC powered hybrid system utilizing an optimization based methodology. Rodatz et al. [63] presented an experimentally applied "equivalent fuel consumption minimization strategy" aiming at minimizing the hydrogen consumption while maintaining drivability in a PEMFC/UC hybrid vehicular system. Xu et al. [64] performed a similar optimization approach for an FC/Battery hybrid bus. Similar fuel consumption minimization based approaches were also utilized by Paladini et al. [65] for FC/Battery/UC hybridization for a vehicle in simulation environment. A model-based optimal control of a PV/FC hybrid power generation system with grid connection was presented by Zervas et al. [22]. A cost-optimized operation of FC power plant was investigated by El-Sharkh et al. [66]. Multi-loop nonlinear model predictive control approach was applied by Chen et al. [38], Wu et al. [28] and Greenwell and Vahidi [67]. Each of the above-mentioned approaches all provided a good contribution to the important energy management issue of PEMFC powered hybrid systems.

These kinds of optimization approaches (especially global optimization methods) are also utilized with different objections in DG units including renewable energy sources like solar and wind, and PEMFC system. The general objective of such studies is obtaining an optimal individual sizing of hybrid system components with minimum cost. Genetic algorithm seems to be the most common approach in the literature for this purpose. Lopez and Agustin [23,24] provided a multi-objective design of a Wind/PV/Diesel/FC/Battery hybrid system by minimizing cost, pollutant emissions and unmet load using genetic algorithm. Besides, Lagorse et al. [26] presented a multi-stage algorithm based on the combination of genetic and simplex algorithms for sizing a street lightening system. Moreover, another method based on particle swarm optimization technique was proposed by Hakimi et al. [25] for the optimum sizing of a Wind/FC powered stand-alone system. Particle swarm optimization approach was also studied by Kaviani et al. [20]. Futhermore, a different approach based on simulated annealing method was investigated by Giannakoudis et al. [27] in simulation environment. Many more studies can be found in a more detailed literature survey.

### 4.3. Frequency decoupling based energy management strategies

During the daily operation of a system, load transitions may occur frequently. Especially, in some applications like vehicular systems, these transient changes in load demand may occur significantly which pose dynamic stress onto the FC membrane due to pressure oscillations and possible oxygen starvation, which may reduce the lifetime of the FC system. Thus, to ensure FC lifetime prolongation by preventing the FC system from load changes with high frequencies, researchers applied different frequency decoupling techniques. The basic approach for this issue is inserting a transfer function for a delay with a suitable time constant (first-order low-pass filter). Liu et al. [68] proposed such a first-order filter for PEMFC system. Besides, some main conventional filtering techniques like Butterworth high and low frequency filters, etc. have been utilized. These conventional filters decouples the main signal with a pre-defined cut-off frequency, thus the FC system can be prevented from transient variations. However, the loss of important edge information is a significant phenomenon in conventional filtering techniques. Considering this issue, some researchers applied a wavelet transform based frequency decoupling strategy for PEMFC powered systems. Wavelet transform is a signal processing method that is well known for its capability to treat transient signals and has been generating increasing interest recently. The advantage of wavelet analysis, as opposed to conventional techniques, is that wavelet transform decomposes a signal into a series of short duration waves or local basis functions (wavelets) on the time axis which allows the analysis of local phenomena in signals consisting of many transients. Besides, wavelet transform provides a quadrate mirror filtering application and the loss of important edge information is minimized compared to conventional filtering techniques. Considering these features of wavelet transform, Uzunoglu and Alam [69] applied a wavelet-based energy management strategy for a PEMFC/UC hybrid vehicular system. A similar wavelet-based approach was utilized by Zhang et al. [39] for a PEMFC/Battery/UC hybrid system. Erdinc et al. [40,41] and Ates et al. [59] also utilized wavelet transform as a part of their energy management approaches.

With the above-mentioned applied types of frequency decoupling strategies, the transients in the total power demand profile are captured, a safe operating condition for FC-based system can be provided and lifetime of the power sources can be extended.

### 4.4. Some other methods for use in energy management

There are many other methods that can be used in the control of hybrid systems and many more new methods will be investigated and take place in the literature in near future. Existing methods in the literature in addition to the before mentioned techniques include basic linear proportional-integral (PI) based approaches and complex adaptive control, robust control, flatness based control, etc. approaches.

A conventional linear PI controller is a basic approach that may be useful for use in real-time implementations of PEMFC systems. Many researchers utilized PI controller especially with a main supervisory controller design. As an example, Thounthong et al. [9,11] utilized a multi-objective PI based linear technique for SOC sustaining and DC link voltage stabilization. Besides, Payman et al. [37,70] applied PI controller for the power electronics converter duty cycle determination in order to regulate the desired values of the system parameters determined by a nonlinear flatness based supervisory control approach. Similar sub-control approaches for regulating the appropriate duty cycles for converters as an

**Table 1**
Brief comparison of energy management approaches applied for PEMFC systems in the literature.

| Energy management approach | Advantages | Disadvantages | Literature studies |
|---|---|---|---|
| Fuzzy logic | Independent from a overall mathematical model, adaptation to more complex structures, computational efficiency, robustness to modelling uncertainties | Dependent on designer's knowledge about the problem | [14,40,41,44,45,53–58] |
| Neural networks | Provides adequate and quick responses to new information | Requires a training procedure | [59–62] |
| Global optimization approaches | Guarantees the optimum solution | Not applicable to real-time applications, not computationally efficient | [20,22–27,66] |
| Local optimization approaches | Applicable to real-time applications | Does not guarantee the optimum solution, not computationally efficient | [28,38,63–65,67] |
| Frequency decoupling techniques | Applicable to real-time applications, provides a load sharing suitable for the individual characteristics of hybrid sources | Does not include the control of multi-objectives if used alone | [39–41,59,68,69] |
| Linear controllers (PI, etc.) | Easy to implement in embedded systems and realize with analog circuits | Not suitable for multi-objective control of complex systems | [9,11] |
| Adaptive, robust, etc. based approaches | Applicable to systems with uncertainties | Robust approach is static and does not adapt to measurement and implementation variations, both techniques require a detailed mathematical knowledge on system | [33,34,71–74] |

assistant to the supervisory main controller were also applied in Refs. [39,40,45], etc.

As another common approach, adaptive control technique involves modifying the control law used by a controller to cope with the fact that the parameters of the system being controlled are slowly time-varying or uncertain. For example, as an aircraft flies, its mass will slowly decrease as a result of fuel consumption; we need a control law that adapts itself to such changing conditions. Adaptive control does not need a priori information about the bounds on these uncertain or time-varying parameters. Besides, adaptive control is precisely concerned with control law changes. There are mainly two types of adaptive controllers: feedforward and feedback adaptive controllers. There also exist many types of feedback adaptive controllers such as Model Reference Adaptive Controllers (MRACs), Model Identification Adaptive Controllers (MIACs), etc. The types of adaptive control method were investigated by many researchers and the studies of Jiang et al. [33], Xu et al. [34] and Zhang et al. [71] can be specified as a small part of literature examples.

Robust control is a branch of control theory that explicitly deals with uncertainty in its approach to controller design. Robust control methods are designed to function properly so long as uncertain parameters or disturbances are within a typical set. Robust methods aim to achieve robust performance and/or stability in the presence of bounded modeling errors. In contrast with an adaptive control policy, a robust control policy is static; rather than adapting to measurements of variations, the controller is designed to work assuming that certain variables will be unknown. The studies realized by Li et al. [72] and Wang et al. [73,74] may be presented as examples for use of robust control method in PEMFC systems.

All the techniques given above include some advantages and as well some disadvantages. Table 1 gives a brief comparison of some of the above-mentioned approaches.

## 5. Conclusions

A PEMFC-based hybrid system should be used as the main substitution for traditional power sources in the near future especially in vehicular, DG and portable applications due to their unique and relative advantages. However without doubt, the technologies of a stable supply of high-purity hydrogen and their associated economical system as well as the expensive cell components are a prerequisite to any other challenge for the market penetration of PEMFC systems for today. This paper presents a detailed overview of the late approaches in hybrid systems including PEMFC technology in concept of application field and energy management as well as the integration topology issues.

Design architecture and energy management in such hybrid structures play a significant role while considering the performance, efficiency and durability issues. Different power electronic interfaces have been investigated by researchers in the design of hybrid PEMFC systems. The trade-off between the complexity of the power electronics circuit and the system performance may provide different results for different types of applications. Besides when the topic is energy management issue, the problems and the solutions take a more important and detailed place in the literature recently. In the field of energy management, most of recent studies focus on applying fuzzy logic based studies. This issue is mainly related with the reasons of easy adaptation to more complex structures, computational efficiency, robustness to modelling uncertainties, etc. Real-time optimization and frequency decoupling methods may also be an alternative choice for online implementation. Moreover, applications of different control strategies are still investigated by the researchers. In short, PEMFC hybrid systems still need research and development studies in many fields and there are still so much work for the researchers to do in order to provide a better market place for PEMFC technology as soon as it is possible.

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